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Turbine Nozzle Guide Vane Exit Area Traversing in a Short Duration Light Piston Test Facility

by

S. P. Harasgama
K. S. Chana

Procurement Executive, Ministry of Defence
Farnborough, Hampshire

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TURBINE NOZZLE GUIDE VANE EXIT AREA TRAVERSING IN A SHORT DURATION LIGHT PISTON TEST FACILITY

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S. P. Harasgama

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SUMMARY

Tests have been performed in the RAE Isentropic Light Pison Cascade (ILPC) facility to measure the total pressure loss of turbine nozzle guide vanes (NGV). A Three-Hole Non-Nulling probe has been utilised with a fast acting traverse which gives a full circumferential sweep over two blade wakes in approximately 500 to 700 ms.

Two types of probes have been used: the first with high frequency response sensors mounted within 25 mm of the probe tip, and the second with low response sensors mounted 500 mm away from the probe tip using lengths of pneumatic tubing.

It is shown that the first probe suffered significantly from probe aerodynamic perturbation due to vibration effects when the air stream was started up in the ILPC. It was found that analogue filtering was required at around 250 Hz in order for the NGV wakes to be distinguished. The wakes extracted after filtering were found to be quite distinct even at one axial chord downstream of the NGV. The second probe was found to be relatively free of aerodynamic perturbations due to the damping nature of the long length of pneumatic tubing between probe tip and transducer.

Results are presented for both probe types which indicate the wake decay between 0.2 and 1.0 axial chords downstream of NGV trailing edge. A full area traverse is also shown which indicates the areas of secondary flow downstream of the blade row.

A paper presented to the 10th International Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines - 17-18 September, 1990, Von Karman Inst. for Fluid Dynamics, Brussels.

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1. INTRODUCTION

The need to improve gas turbines to increase reliability and reduce running costs has led to the development of experimental rigs to examine the behaviour of individual components. One such test facility is the Short Duration Isentropic Light Piston Cascade (ILPC) at RAE Pyestock. A detailed description is given in Ref 1. A schematic of its principal components is shown in Fig 1. The ILPC provides full similarity with modern high pressure turbines with respect to Mach numbers and Reynolds numbers as well as freestream to wall temperature ratios. The fully annular facility is designed to investigate aerodynamics and heat transfer of modern high pressure nozzle guide vanes (NGVs). The duration of a run varies from 0.5 to 1.5 seconds, depending on the running condition.

The desire for further performance measurements has led to the development of 3 hole probes for wake traversing at exit from NGV's, this would allow the investigation of total pressure loss. The probe traverse speed is of the order of 200 mm/s during the facility runtime. During this period the probe traverses 2 complete wakes, at a preset radial location.

The development of the Non-Nulling 3 hole area traversing probes comprised of 2 phases:

a. The development and testing of a high frequency response pressure probe

b. The development and testing of a low frequency response probe.

A fast acting mechanism was used to traverse the probe circumferentially. A stepper motor was used for positioning the probe at various radial locations. During the traverse, data was simultaneously recorded on both a low-speed and high-speed data acquisition system.

The high response probe was tested on the High Rim Speed Turbine (HRST), Ref 2, NGVs at design Mach number and Reynolds number. The low response probe was tested on HRST NGVs with profiled endwall (PEW), again at design Mach number and Reynolds number.

During all tests, static pressure tappings on 50% vane profile suction/pressure sides and exit hub/casing were monitored for probe blockage effects.

2. INSTRUMENTATION AND DATA ACQUISITION

The 3 hole probe was mounted within an actuation system which enabled accurate circumferential and radial positioning. Position sensing was achieved by use of linear variable differential transformers (LVDT), one for each circumferential and radial displacement. The probes used 3 transducers each, the high response probe utilised 3 ENDEVCO[1] transducers with a response up to 300 kHz. The low response probe was fitted with National Semiconductor[2] pressure transducers.

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[1] Endevco - Registered Trademark of Endevco Corporation, California, USA.

[2] National Semiconductor - Registered Trademark of National Semiconductor Corporation, California, USA

All transducer and LVDT outputs were processed through signal conditioning units prior to digitisation. LVDT outputs were pre-amplified before digitisation. The output of the ENDEVCO units were pre-amplified and subsequently low pass filtered at 3 kHz before digitising. Amplification was required because the output of ENDEVCO transducers was around 300 mV maximum. The National Semiconductor transducers yielded around a 4 volts output and only required slight pre-amplification prior to digitising.

All outputs were digitised on low speed (4 kHz) and high speed (up to 2 MHz) analogue-to-digital (A/D) subsystems. Each A/D system enabled a resolution of 4.88 mV per bit accuracy. After the run data was transferred to the PDP11/24 rig computer for preliminary analysis. Detailed analysis was performed on the departments VAX 11/780 after a full area traverse was obtained. All data transfer from the PDP11/24 to the VAX were via a site wide ETHERNET network. Work is now underway to replace the PDP11/24 with a Concurrent/Masscomp computer which will allow all real time and detailed analysis to be performed simultaneously. This will obviate the need to transfer data to the VAX and thereby speed up the analysis procedure. During the traverse/testing phases a 2 channel 100 MHz digital oscilloscope was used for a quick check of traverse and run-time synchronisation. Fig 2 shows a schematic of the overall instrumentation system.

2.1 Probe Details

Probe Tip Construction

The high frequency probe was designed to house 3 Endevco pressure transducers, 1 total pressure and 2 yaw pressures. The Endevco's were fitted 25 mm from the tip of the probe. The construction of the low frequency probe was similar to the high frequency response probe but instead of Endevcos being fitted in the hyperdermic tubing, plastic tubing was attached to the steel tubing and passed through the body of the probe and connected to National pressure transducers. The plastic tubing was approximately 500 mm long. A swan neck probe was also developed to enable traverses close to the inner wall, see Fig 3. This was tested on HRST/PEW NGVs. The probe tips were constructed using 3 steel hyperdermic tubes 2 mm outer diameter. The Endevco's were fitted into these tubes. The tip was then mounted into a brass head. The brass head would then fit into the probe body. The probe tips were constructed with the 2 yaw holes normal to the probe local surface as shown in Fig 4. It has been shown by Fransson et al (Ref 3) that this type of tip design will reduce unstable behaviour of the calibration curves and any high frequency effects.

Static Calibration

The Endevco pressure transducers were static calibrated for the evaluation of conversion factors. The static calibration was performed with the Endevco's in situ in the probe tip using a Dead Weight Tester (DWT). The National pressure transducers were static calibrated with the DWT while disconnected from the probe.

Probe Calibration

A 9" by 3" induced flow tunnel at the Osney Laboratory, Oxford University was used for the calibration. For a detailed description of the tunnel see Ref 4. The probe was mounted in the tunnel fixing it to the working section window. The correct alignment of the probe was critical for an accurate calibration. This was achieved by aligning an optical cross hair with the tunnel wall and ensuring a thin straight rod located in the centre hole of the probe was parallel to the cross hair. The window could then be rotated using a calibrated vernier attached to the window, to set any probe tip angle between ± 10° to the flow. Fig 5 shows a schematic of the working section with the probe installed. Calibrations were then performed for Mach numbers of 0.95, 1.05, 1.15 and 1.20 at yaw angles of 2 degree intervals over the range -10° to +10°. Figures 6 and 7 show yaw and total coefficients plotted against yaw angle (THETA) for all 4 Mach number conditions.

A Schlieren system was used during calibration to visualise the shock structure around the probe tip, no reflected shock structures at extreme yaw angle of ± 10°, which would affect probe readings were seen, results of the Schlieren tests can be seen in Fig 8.

2.2 Traverse Mechanism

The traverse gear which allows both radial and circumferential traversing consists of an annular ring which is supported such that it may be rotated within the vane ring assembly. It may therefore be fixed in position to traverse behind any vane passage. The fast actuation is achieved using a pneumatic cylinder, see Figs 9 and 10. The two extreme positions are shown, an 18° arc of rotation of the probe is achieved. The speed of traverse can be very accurately controlled between 100 ms and 1.5 seconds, using adjustable needle valves on the actuator exhaust ports. These can be adjusted to change the traverse speed in any direction. The geometry of the probe is designed such that when connected to the traverse ring the tip remains parallel to the endwalls.

The circumferential LVDT is mounted on the actuator and connected to the actuator ram, this gives an accurate change of the ram position and hence the probe position. The radial movement of the probe to a particular radial position is achieved using a stepper motor, see Figs 10 and 11, the radial LVDT is fixed to the side of the radial drive and connected to the probe stem, this gives an accurate change in radial position. The LVDT's are calibrated to give a voltage/displacement factor.

The traverse gear trigger system was built with a variable start delay time. This is used to synchronise the rig runtime to the traverse start time. The traverse is delayed by approximately 100 ms after the run starts, this allows the flow to establish before traversing begins.

3. RESULTS AND DISCUSSION

The high response and low response pressure probes were installed in the test facility at 1.0 and 0.2 of an axial chord downstream of the NGV exit plane respectively. The vanes were operated at design conditions with a Mach number of 1.14 and Reynolds number of 3.4×10^6 based upon exit conditions and vane tangential chord. A full area traverse from 22% to 91% radial heights were covered, at 1.0 axial chord and from 8% to 91% radial heights at 0.2 axial chord. Radial locations were chosen to achieve more detail nearer the endwalls than mid-passage. To keep experimental error to a minimum the Reynolds number and Mach number were matched to within 3% from run to run.

3.1 Tests at 1.0 Axial Chord (High Response)

A single unfiltered, unprocessed total pressure traverse trace in the flow direction, at mid height is shown in Fig 12. Clearly no wakes are visible here, the signal being very noisy.

Data from the centre hole Endevco transducers, recorded on the high speed A/D system, was analysed using a Fourier transform and the power spectrum examined. Figs 13 and 14 show that the frequency response is fairly flat up to 3 kHz where the filter cut-off was set. Very little attennuation is seen between DC to 3 kHz. Clearly the probe response is therefore satisfactory and it is quite possible that the probe is suffering some vibration which results in "aerodynamic" noise being superimposed on the actual signal. Fig 13 shows the first 1024 point FFT of the proble whilst Fig 14 shows the second FFT taken from 1024-2048 points of the digitised trace. Since the two spectrums are very similar, the noise levels appear to have swamped the effects of the NGV wakes.

Static pressure measurements on the vane profile were used to check Mach number distribution during probe traverses, Mach numbers without and with traverse showed no probe blockage. Similarly static pressure tappings on the vane hub and casing downstream of the trailing edge plane showed no blockage effects. The lack of probe interference is attributed to the probe being one axial chord downstream of the NGV trailing edge plane.

3.2 Tests at 0.2 axial chord (Low Response)

The low response probe was orginally designed to traverse at 0.4 axial chord. However when it was installed and tested the probe tip was misaligned to the mean exit flow angle of 70°. This can be seen by the difference in the two yaw pressures in Fig 16a. The probe was then adjusted to the correct exit angle causing the proble tip to move closer to the NGV trailing edge plane and because of the 'lever-arm' effect the probe was then at 0.2 axial chord. Fig 16b shows the yaw pressure after correction, some small differences still exist but are not considered to be significant.

The low response probe suffered very little noise problem as can be seen in Fig 16, the total pressure trace clearly shows wakes and filtering at 250 Hz showed little difference to the unfiltered signal. The wakes are much more pronounced as expected at 0.2 axial chord.

As with the high response probe tests, static pressure tappings on the vane profile, hub and casing were measured during probe traversing. The vane profile tappings showed no disturbances on both suction/pressure sides, but static pressure tappings on the hub and casing show considerable blockage. Fig 17a shows inner wall static pressure measurements with and without probe traverse at various radial locations. The blockage was attributed to the probe body, so to avoid measuring disturbed flow the probe was traversed into the flow. Fig 17b shows a cross-section showing the traverse plane and the static pressure measurement point. Fig 18 shows 50% vane profile Mach number distribution with and without traverse. A closer look at the disturbed static pressure shows the blockage is started once the body of the probe passes the static measurement point, indicating disturbances are due to the body of probe and not the tip.

3.3 Analysis of Data

Figs 19 and 20 show unprocessed circumferential total pressure at various radial heights for both 1.0 and 0.2 axial chord tests. The wakes can be seen to move from hub to casing following the vane trailing edge curve.

Software was developed to analyse the raw data, the analysis performed is outlined below.

During a run the air passing over the vanes raises the dump tank pressure thereby leaving the dump tank at a higher pressure than initially. This change in dump tank pressure is measured during the run and subtracted from the total and yaw pressures measured by the probe.

The total pressure measured at inlet to the vanes varied from run to run by around 4%. In order to compare data from different runs, pressures were normalised relative to the ratio of maximum upstream total pressure for all runs and the upstream total pressure for any particular run.

The yaw holes in the probe tip lie in a horizontal plane with a small separation of 2.02 mm between each hole. The pressure measured by each hole is therefore in a different circumferential position. The data was corrected for probe tip size by interpolating the data to the same circumferential position, the interpolation is by a cubic spline method.

The measured pressures have superimposed piston oscillations and some electrical/ aerodynamic noise. To eliminate this a running average was taken of the data. A 4 point average was used for the results presented in this paper.

Finally, the processed data is utilised to evaluate yaw and total pressure coefficients from which exit total pressure, Mach number and yaw angle are derived. The calibrations shown on Figs 6 and 7 (Section 2.1) were used for the analysis.

Typical processed total pressure data for the 1.0 axial chord traverse are shown on Fig 21 for radial heights of 25%, 50%, and 80%. It can be seen that the processed data produce good quality results from which the aerodynamic loss of the vane row may be evaluated. The mixed out profile loss at mid-span is estimated to be about 7.5%. From present experience it is considered that the error on the loss estimate is around ± 10%. Work is underway to obtain more detailed and accurate traversing to improve the error margin, with a target value of 0.20% being considered to be achievable. It is thought that more detailed calibration of the probe will yield more accurate results.

Mach number and yaw angle results for the 1.0 axial chord tests show that there is a reduction in Mach number through the wake as expected. The yaw angle variations are also as expected, with the flow angle varying from positive to negative values about the mean flow field.

Typical processed total pressure plots for the 0.2 axial chord traverse are shown on Fig 22. These results have not been processed through the calibration routines for yaw and total pressure coefficient and results are not yet available for Mach numbers and flow angles. However, the plots indicate a steeper gradient of total pressure in comparison to the traverse at 1.0 axial chord (Fig 21) because the wakes are less mixed out in this case. A full area representation of the wake traverse at 0.2 axial chord is shown on Fig 23. It can be seen that the total pressure deficit repeats with the vane pitch. These results indicate that quite detailed area traverses can be obtained in the ILPC. Fig 24 is a full area plot of the total pressure deficit as computed with a three-dimensional steady state Navier-Stokes flow solver using the mixing length turbulence model, (Dawes, 1986). The experimental results of Fig 23 compare quite well with the prediction of Fig 24. However, due to the physical size of the probe it was not possible to obtain results closer to the endwalls.

4. CONCLUSIONS

A capability for downstream area traversing has been developed for the evaluation of turbine vane total pressure loss in a full annular cascade within a short duration test facility.

High response and low response Three-Hole probes have been tested and it is shown that a low response system is adequate, providing a frequency response of at least 250 Hz is achieved. The present system is estimated to be able to evaluate total pressure losses to an accuracy of 10%. Work is underway to improve the accuracy of the measurement system to around 0.25% or better. Results show reasonable agreement between predictions and experiment. Future probes and traverse systems will enable detailed measurements of loss and secondary flow features downstream of the vanes.

Acknowledgements

The involvement of the turbomachinery group at the Osney Laboratories, Oxford University in the design and manufacture of the measurement systems is gratefully acknowledged.

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No	Author	Title etc
1	Brooks, A.J.	The isentropic light piston cascade facility RAE Technical Report 85098 (1985)
2	Kingcombe, R.C. Harasgama, S.P. Leversuch, N.P. Wedlake, E.T.	Aerodynamic and heat transfer measurements on blading for a high rim-speed transonic turbine. ASME Paper No: 89-GT-228
3	Fransson, T. Sari, O.	Characteristics of aerodynamic five-hole probes in transonic flow regions. Proceedings of the 6th Symposium of Flow Measuring Techniques in Transonic Flows in Cascades and Turbomachines, Lyon, 1981
4	Wagstaff, M. Vardy, H.	Calibration of Three-Hole Yaw Probe Final year project report. Oxford University, Spring 1985

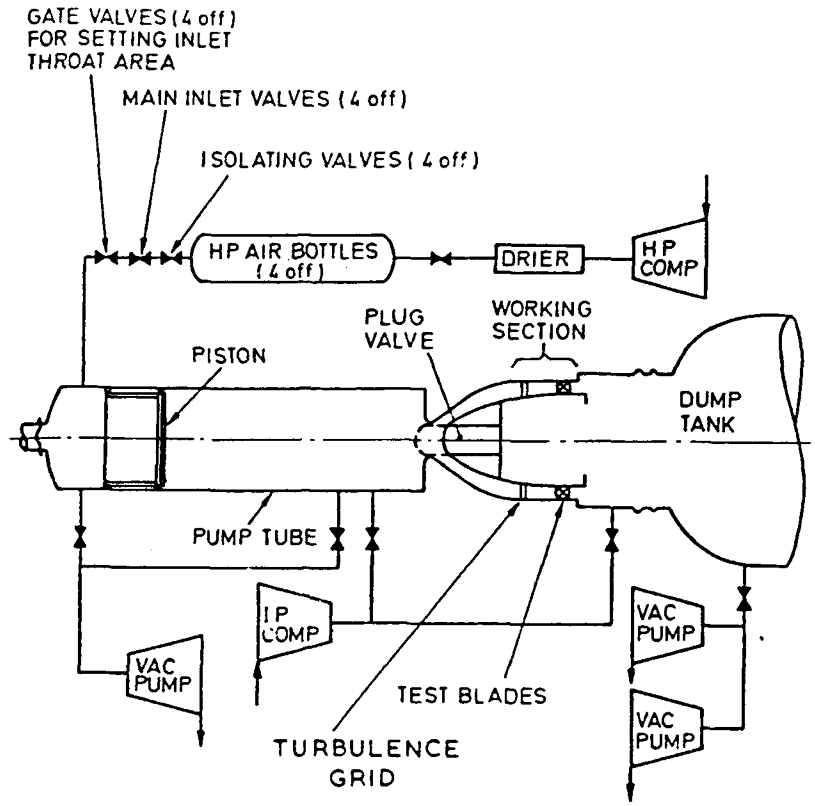


FIGURE 1 THE ILPC TEST FACILITY

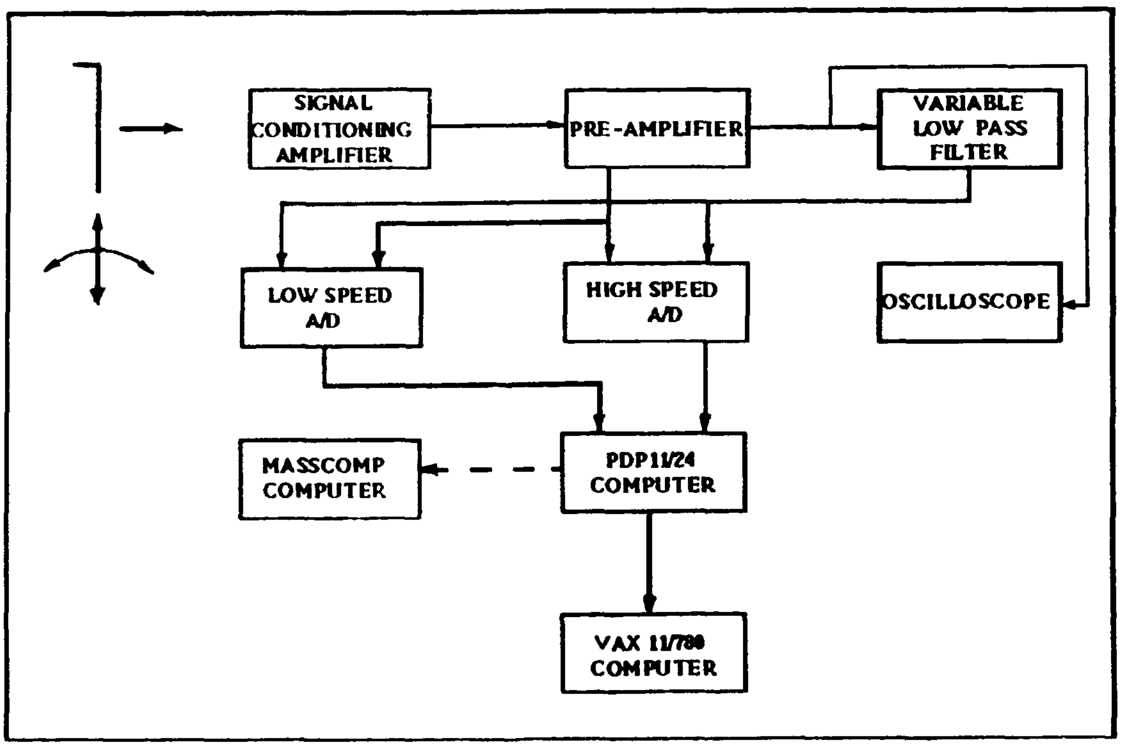


FIGURE 2 OVERALL INSTRUMENTATION SYSTEM

FIGURE 3 SWAN NECK PROBE

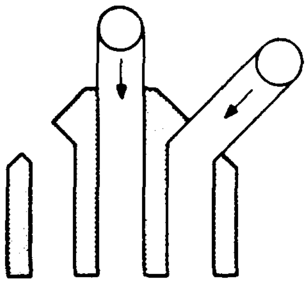


FIGURE 4 PROBE TIP DESIGN

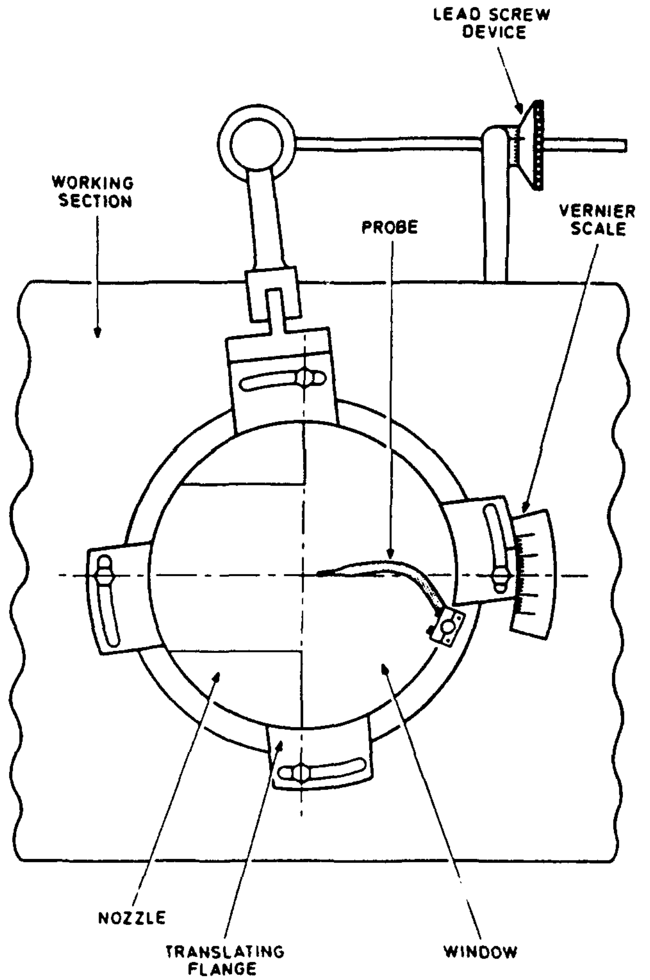


FIGURE 5 CALIBRATION TUNNEL WORKING SECTION

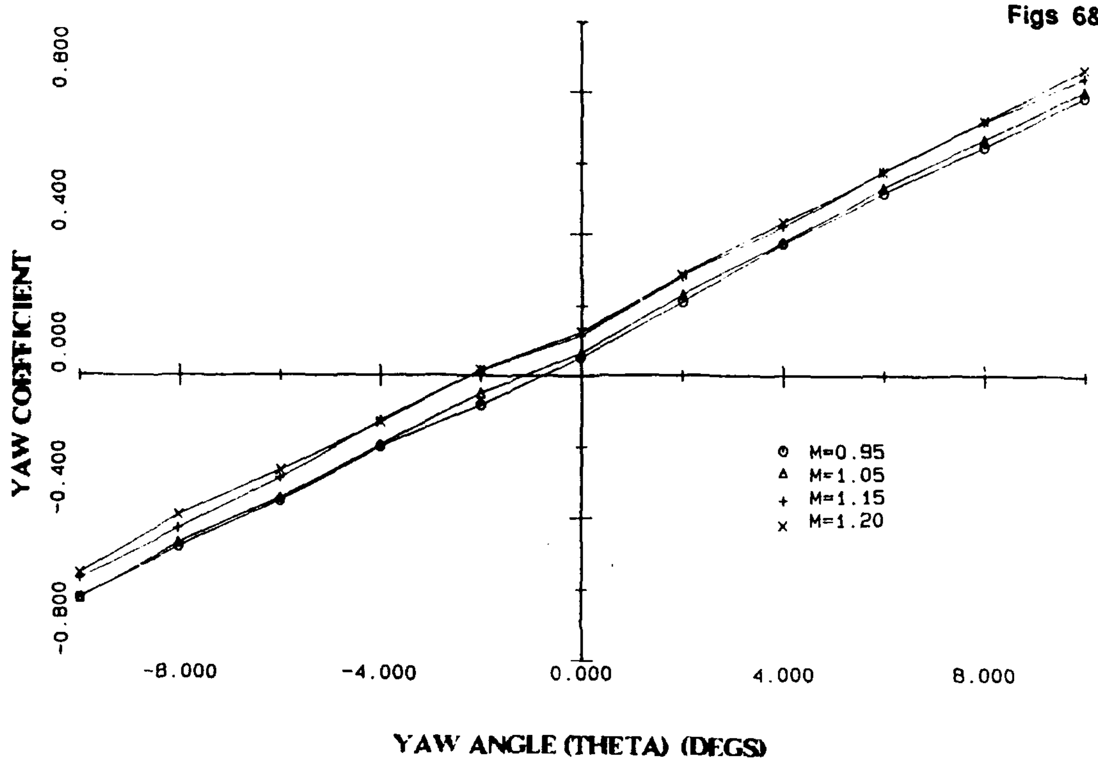


FIGURE 6 PROBE YAW PRESSURE COEFFICIENT

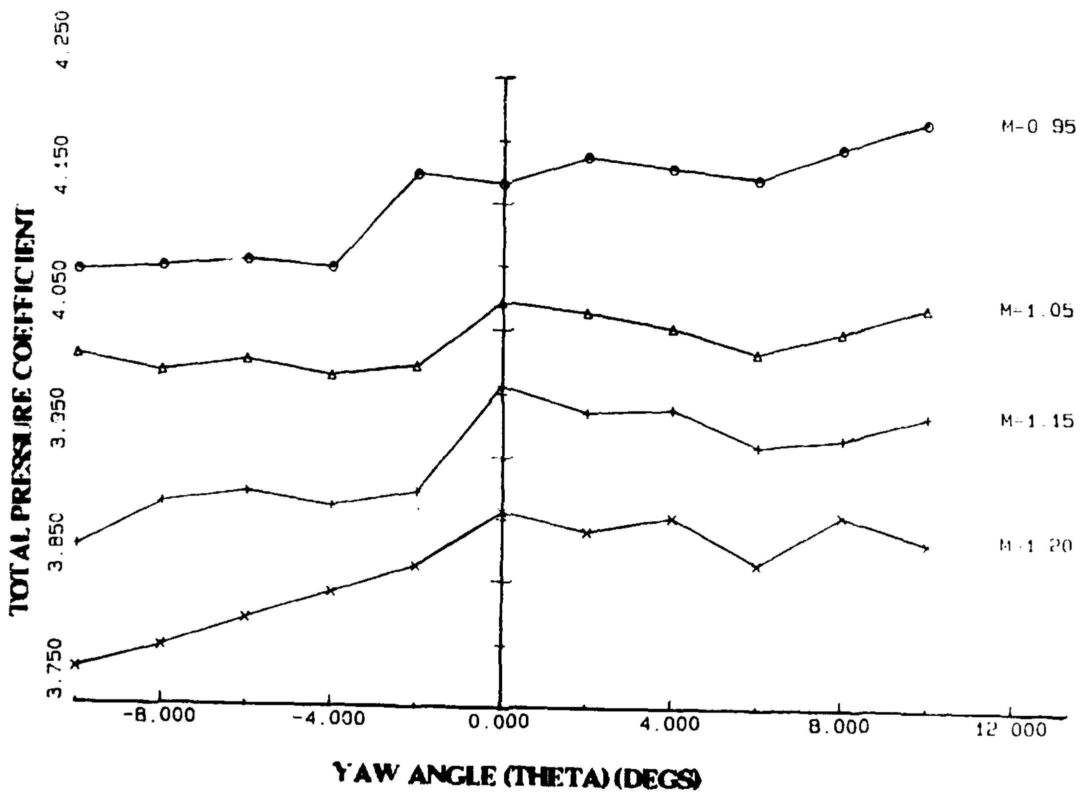
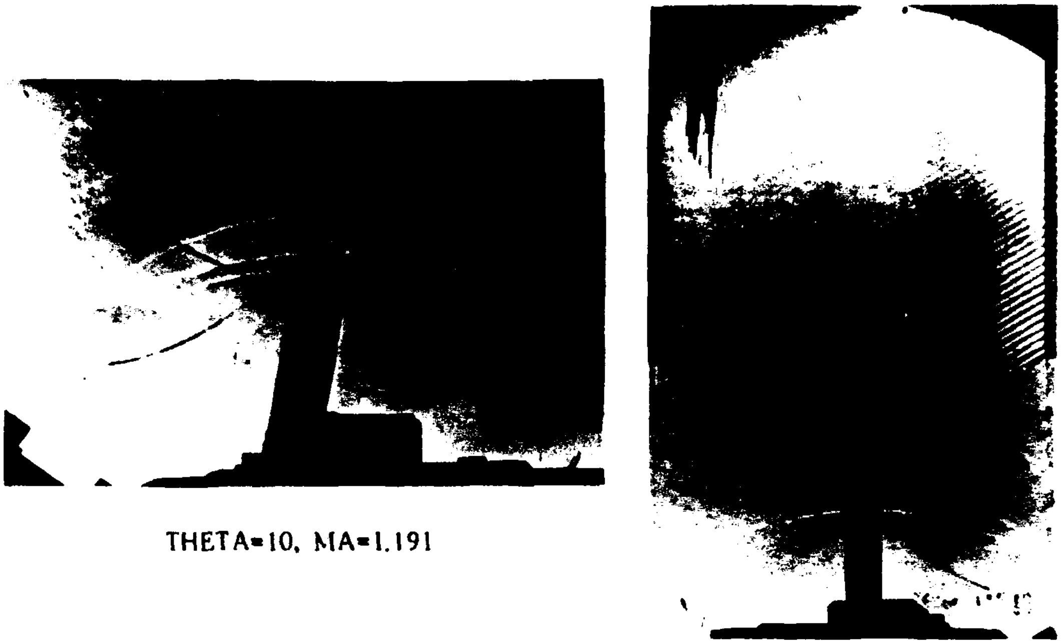


FIGURE 7 PROBE TOTAL PRESSURE COEFFICIENT

Figs 8&9



THETA=10, MA=1.191

THETA=0, MA=1.198

FIGURE 8 SCHLIEREN PHOTOGRAPHS

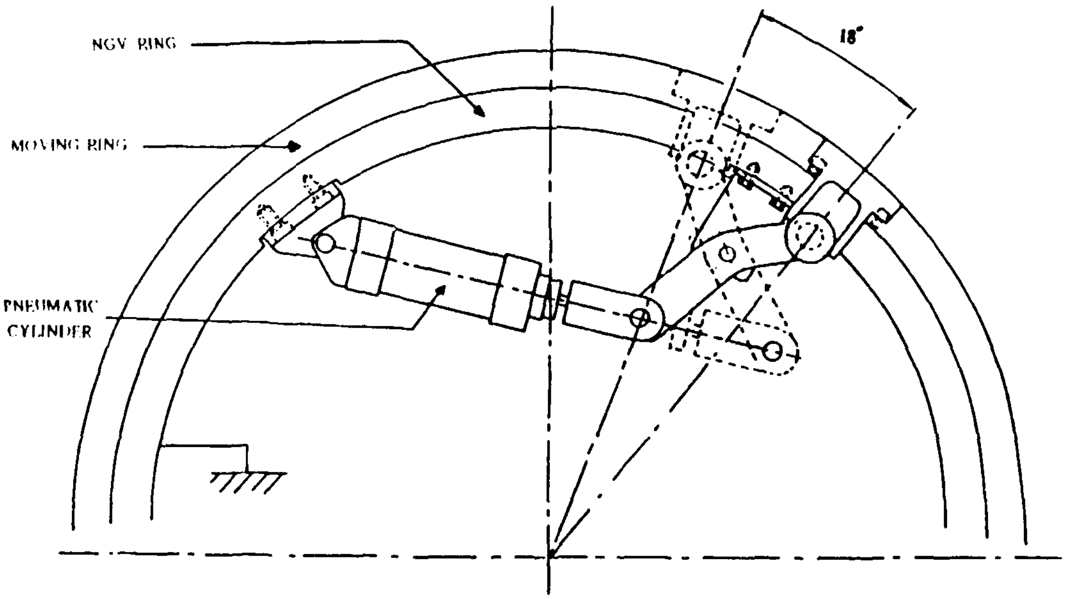


FIGURE 9 CIRCUMFERENTIAL TRAVERSE MECHANISM

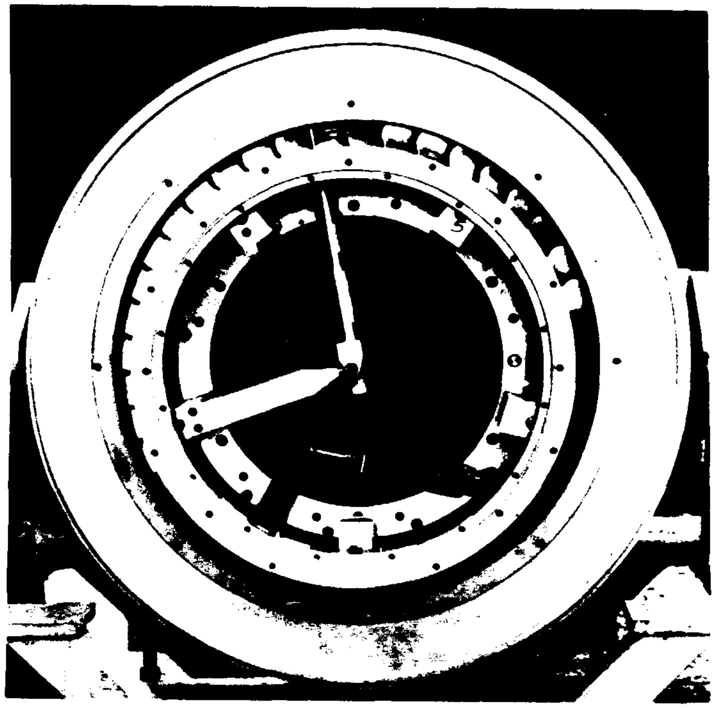


FIGURE 10 PROBE INSTALLED IN TURBINE RING

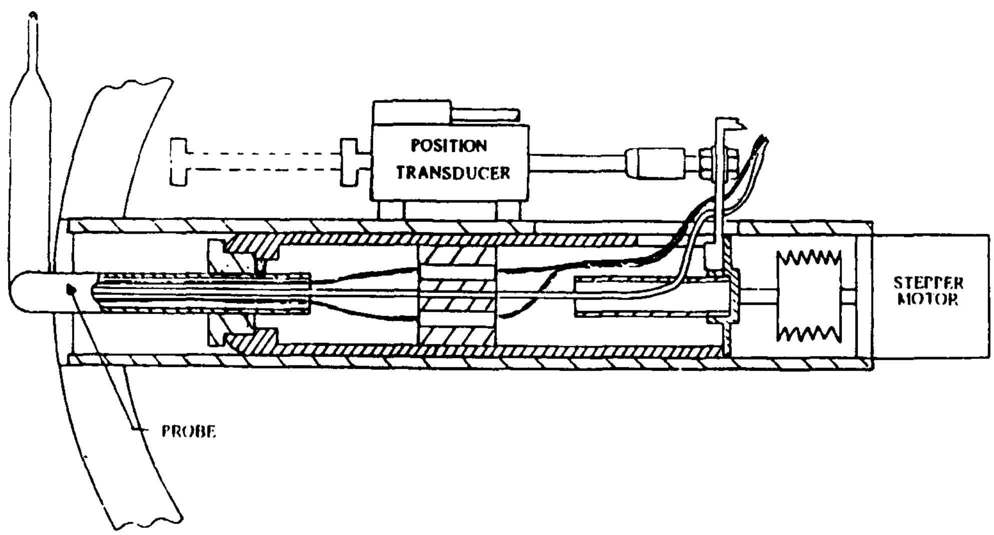


FIGURE 11 PROBE RADIAL DRIVE

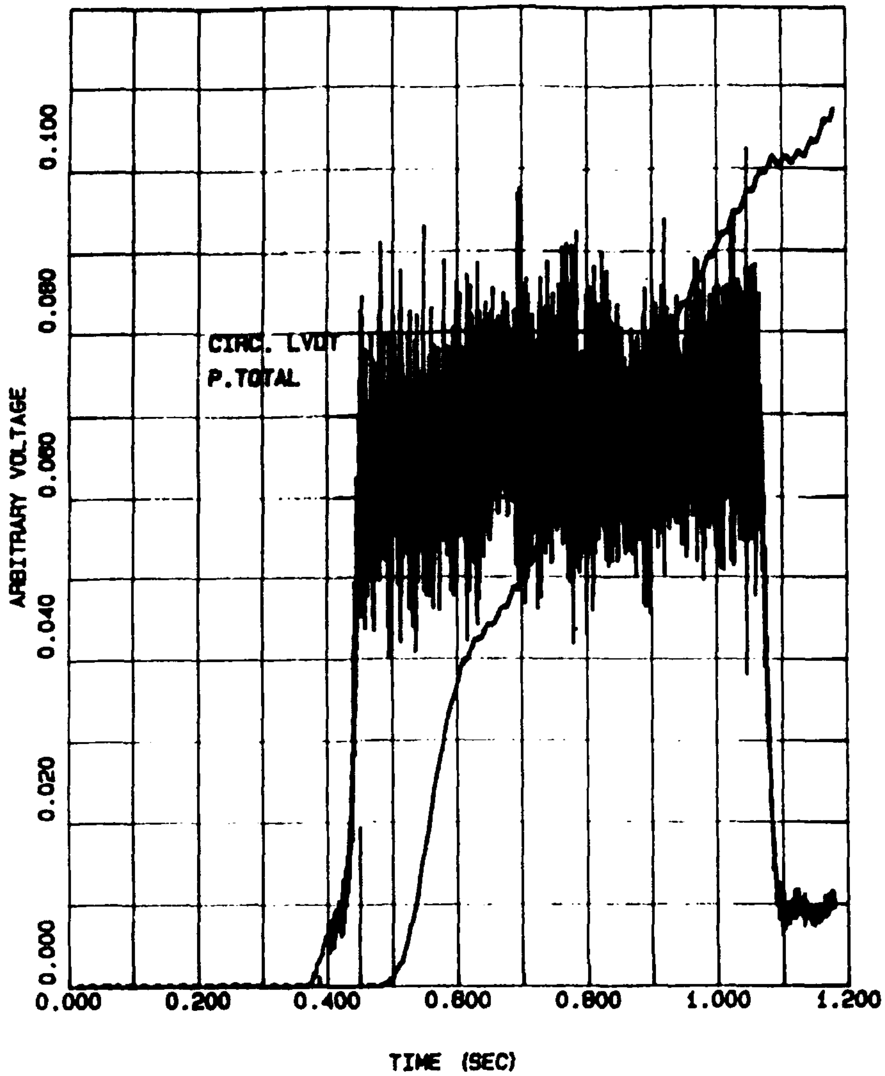


FIGURE 12 UNFILTERED TOTAL PRESSURE

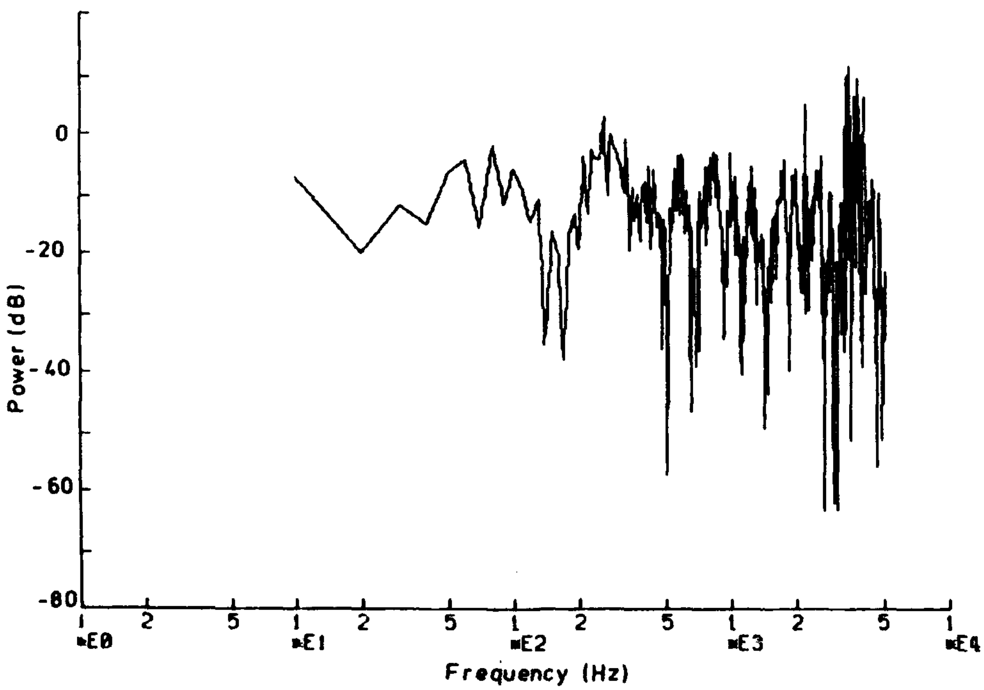


FIGURE 13 POWER SPECTRUM OF TOTAL PRESSURE (0-1024)

Figs 14&15

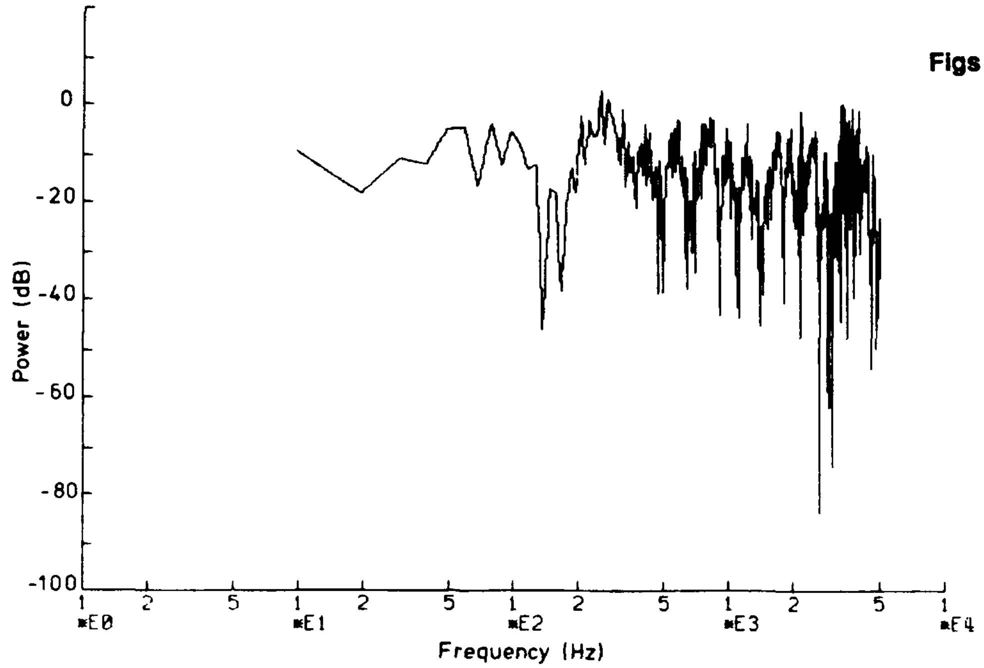


FIGURE 14 POWER SPECTRUM OF TOTAL PRESSURE (1024-2048)

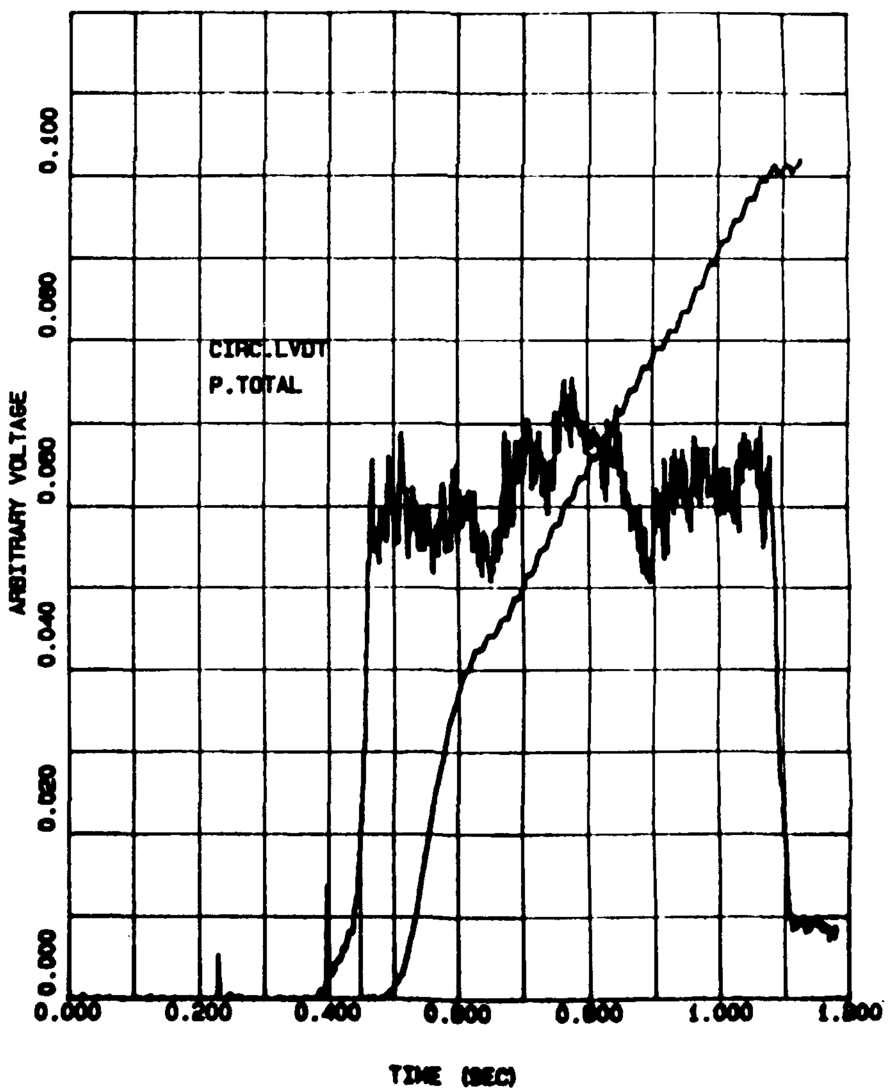


FIGURE 15 FILTERED TOTAL PRESSURE (250HZ)

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Fig 16a&b

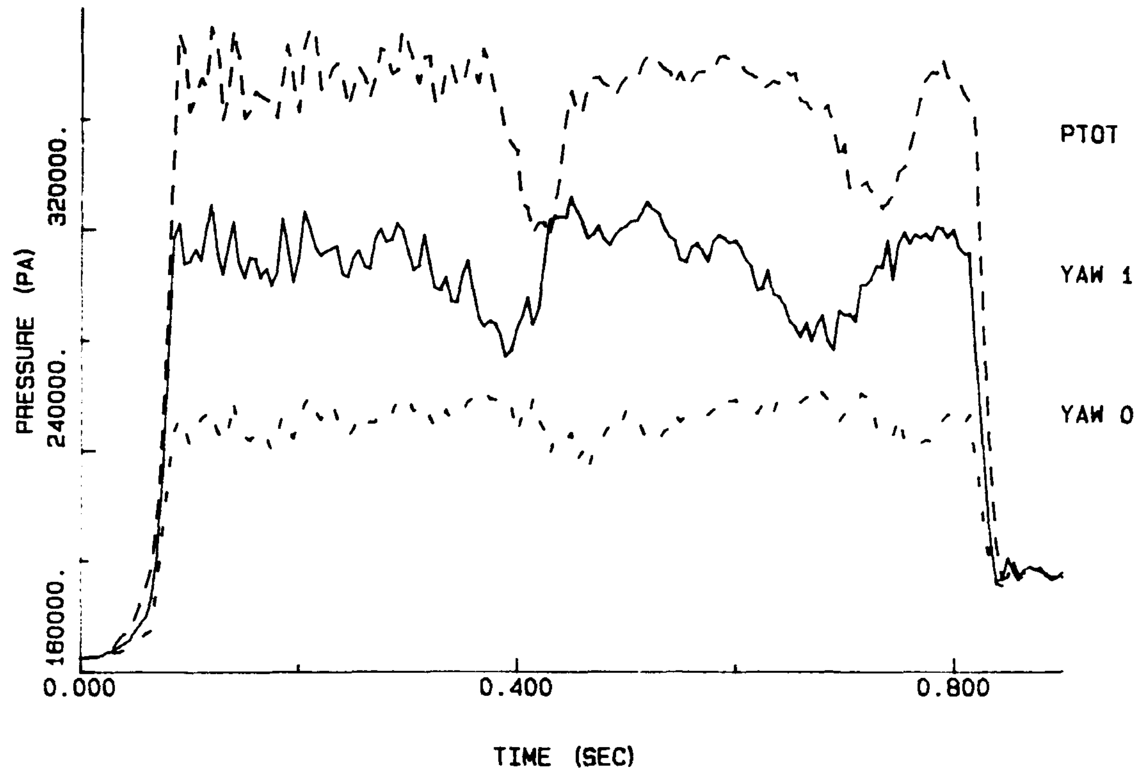

FIGURE 16A DIFFERENCE IN YAW PRESSURES

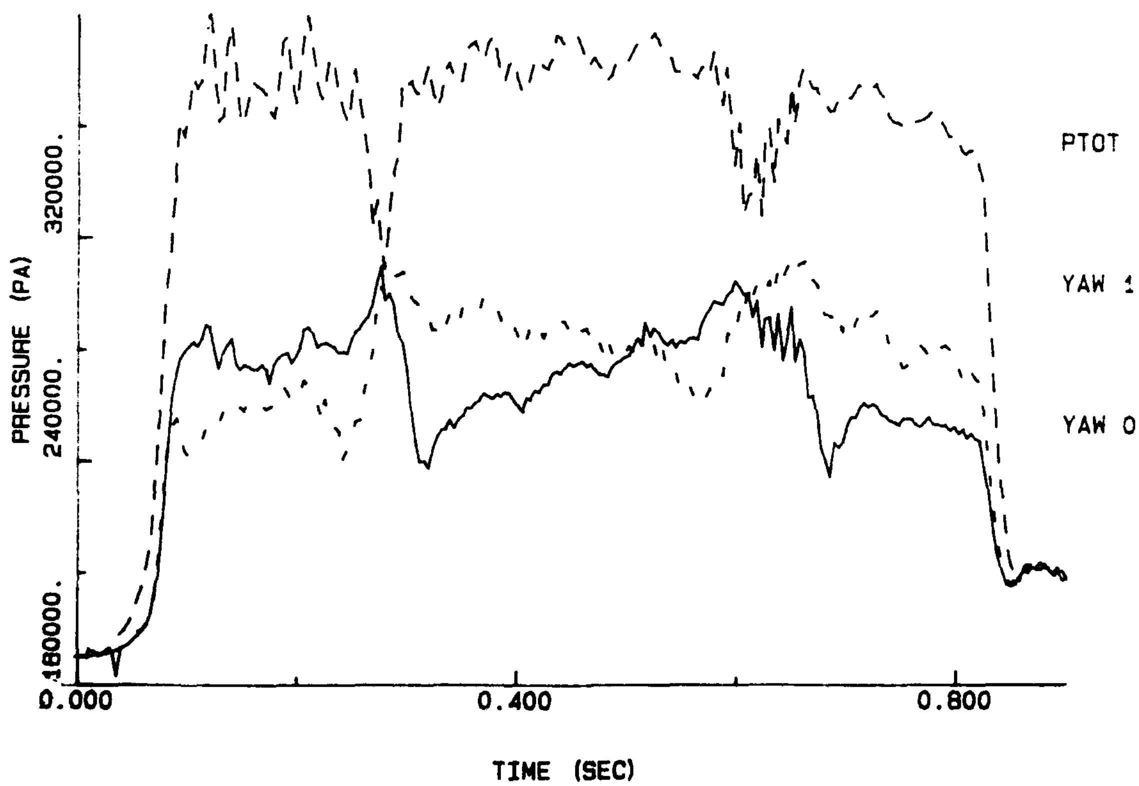

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FIGURE 16B CORRECTED DIFFERENCE IN YAW PRESSURES

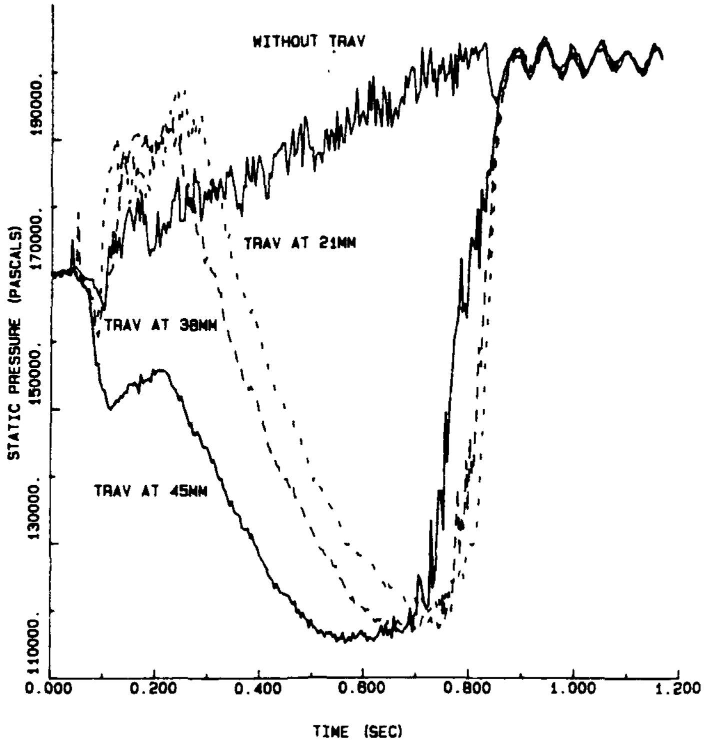

FIGURE 17A INNER WALL STATIC PRESSURE

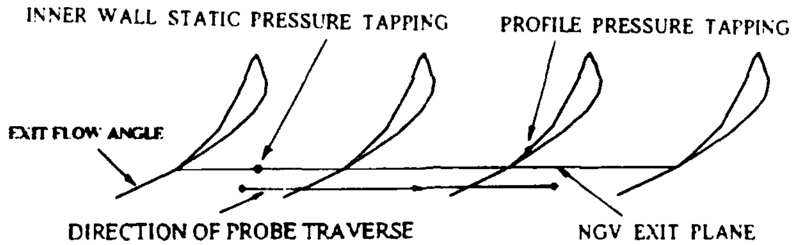

FIGURE 17B SCHEMATIC OF MEASUREMENT PLANE

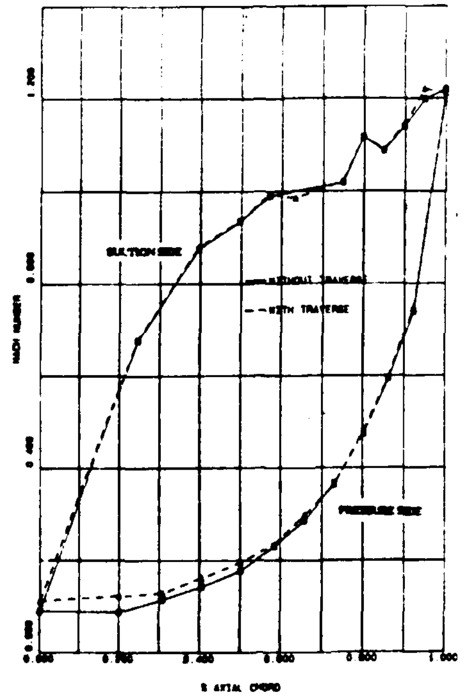

FIGURE 18 50% VANE PROFILE MACH NUMBER DISTRIBUTION

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Fig 19

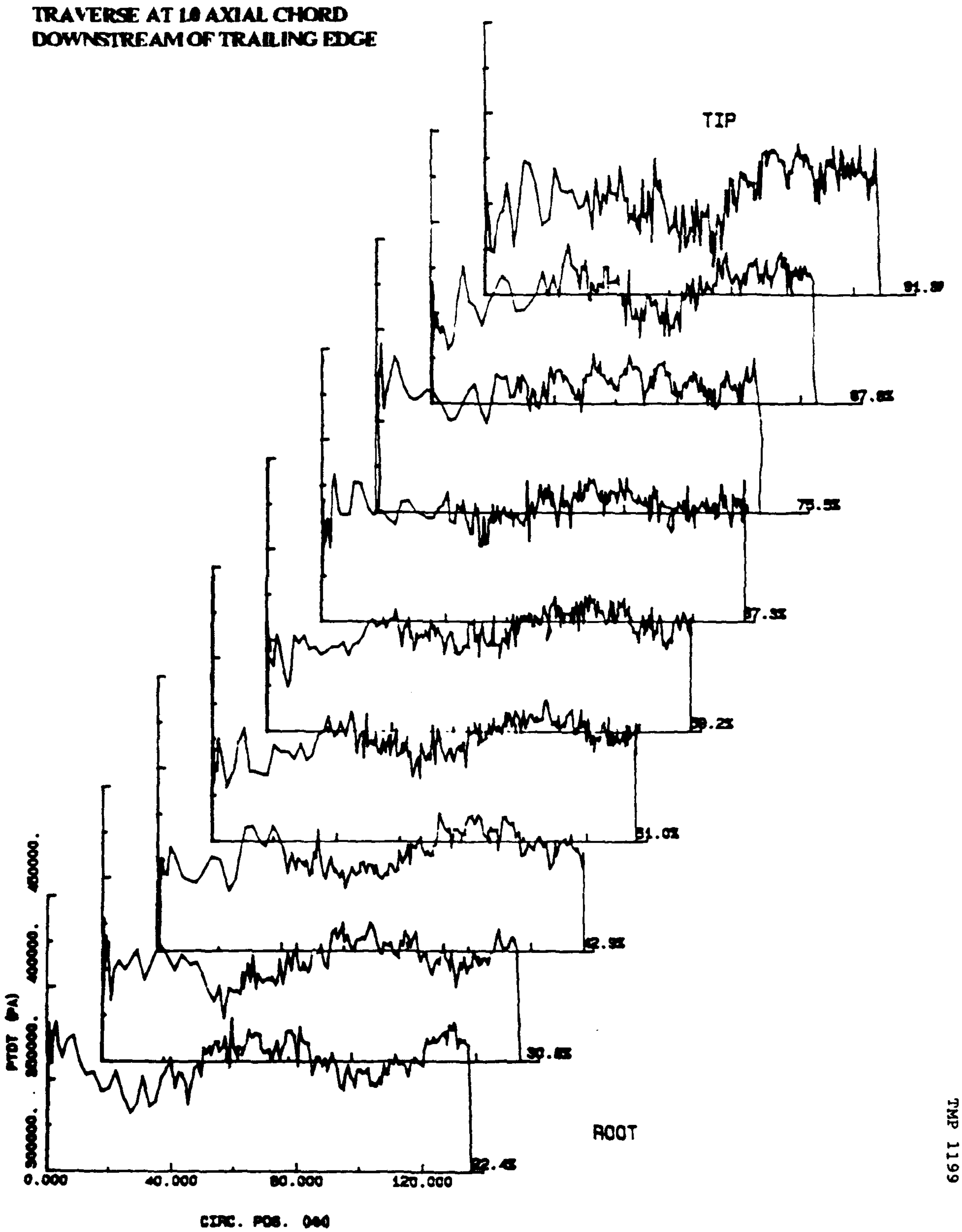

FIGURE 19 TOTAL PRESSURE (HRST VANE)

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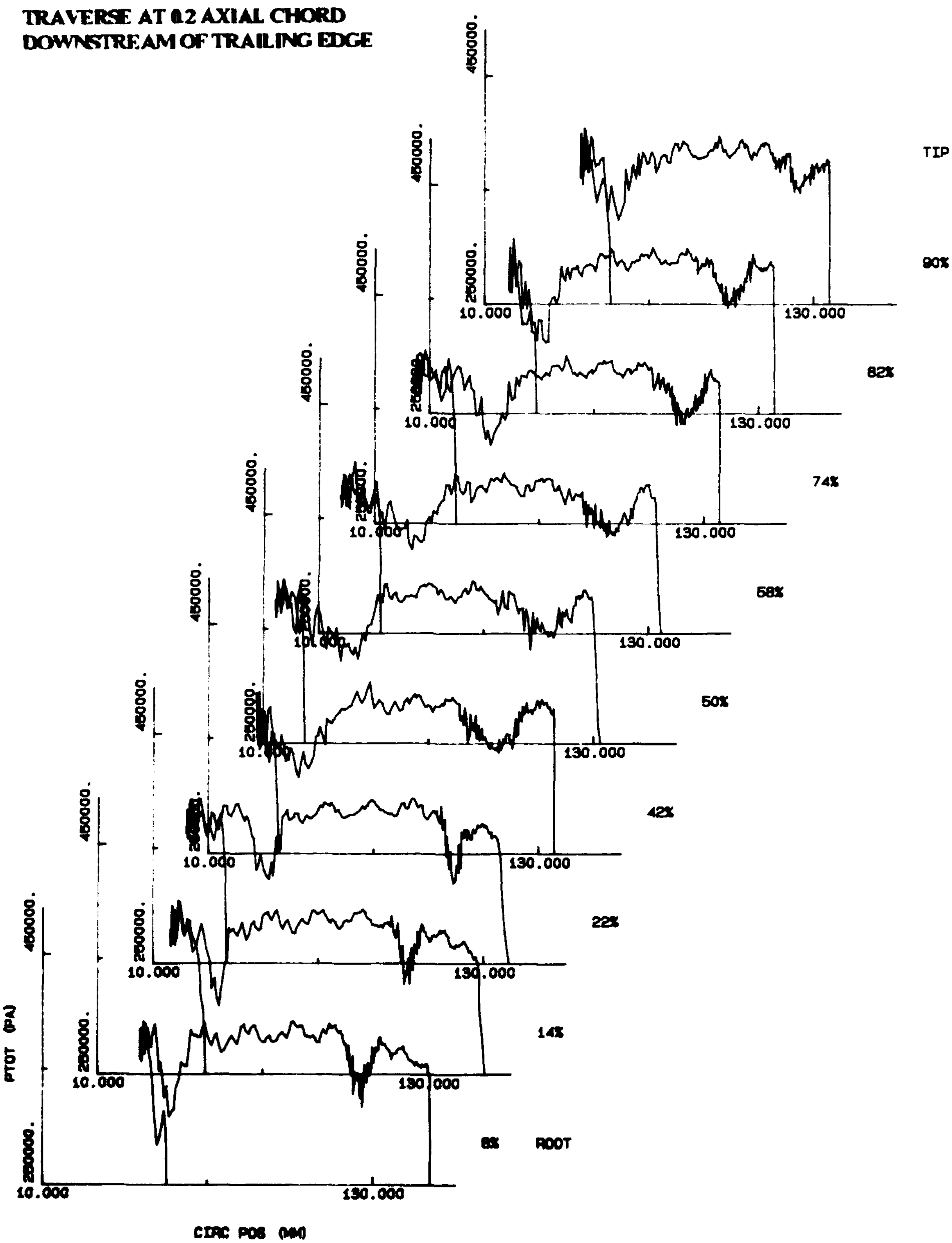

FIGURE 20 TOTAL PRESSURE (HRST/PEW VANE)

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Fig 21

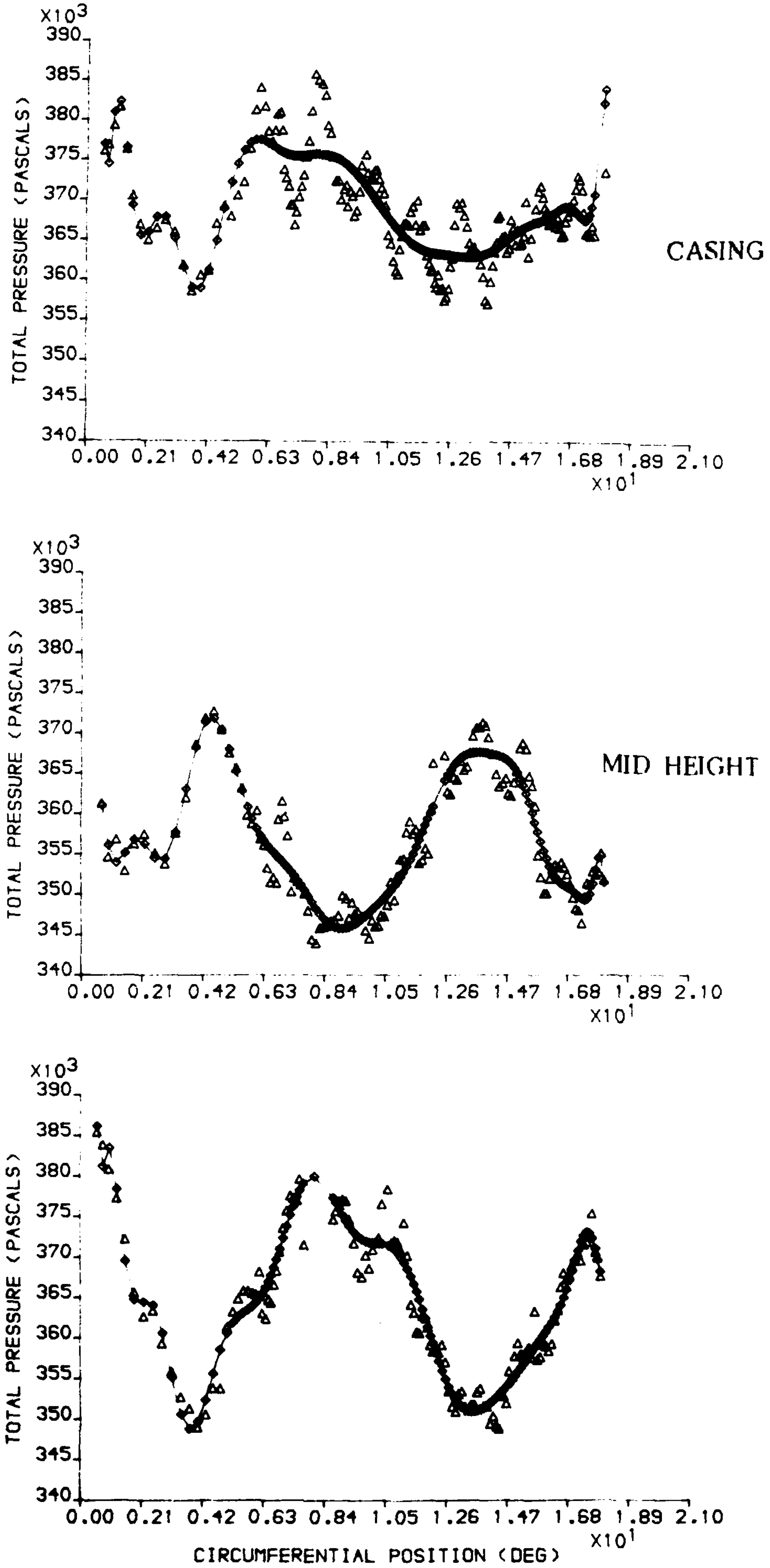
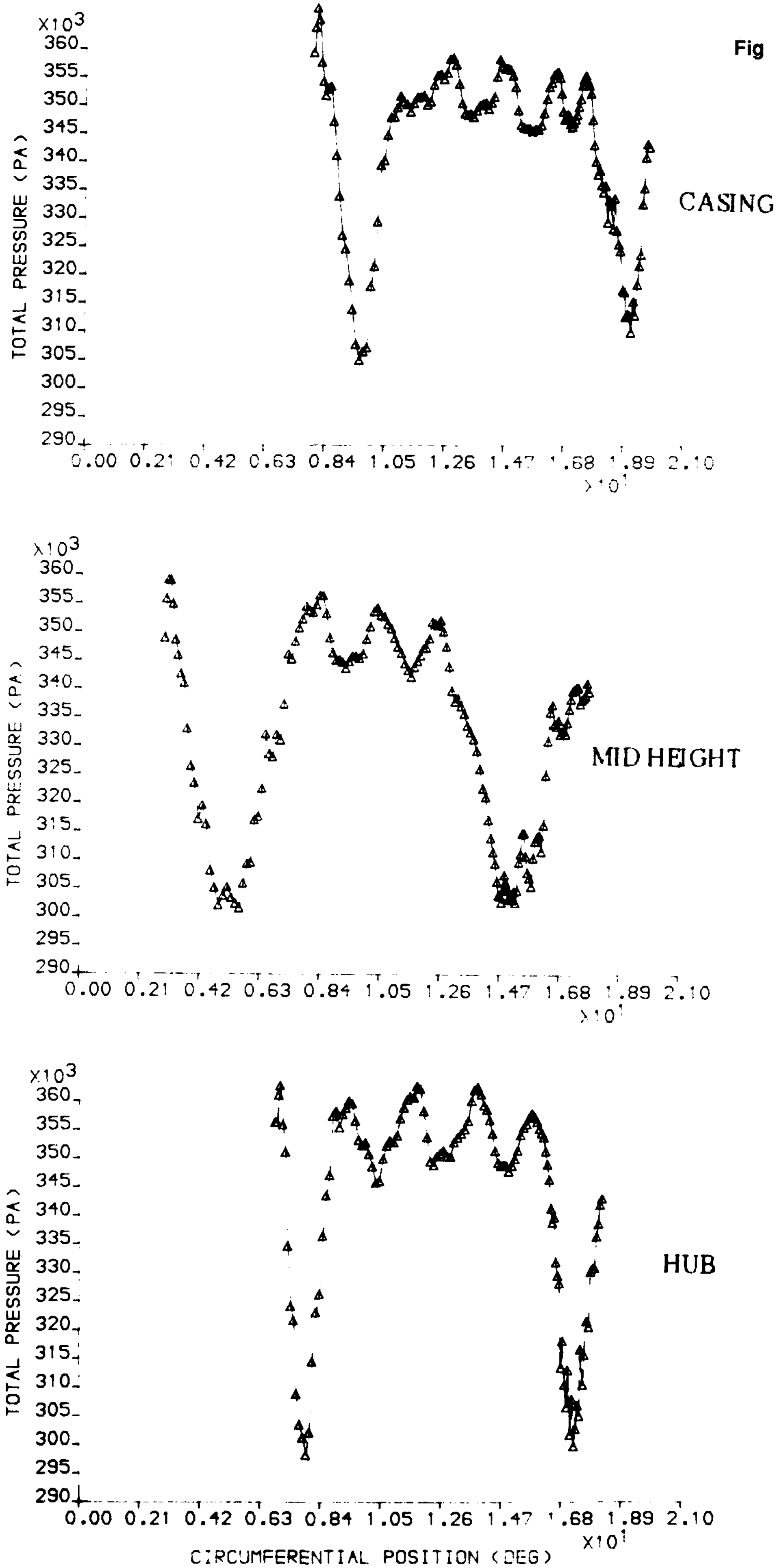


FIGURE 21 PROCESSED TOTAL PRESSURE (HRST VANE)

Fig 22



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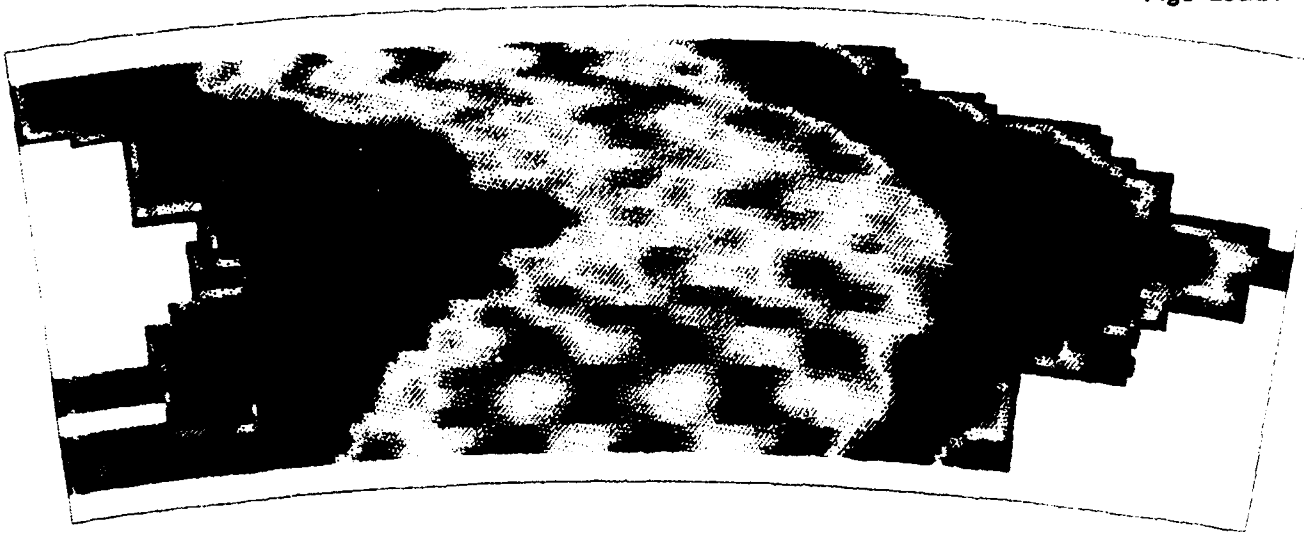
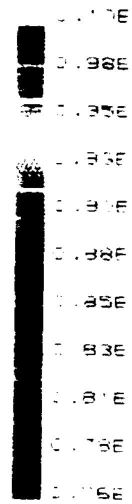


FIGURE 23 FULL AREA TRAVERSE (HRST/PEW VANE)



NON-DIMENSIONAL TOTAL PRESSURE CONTOURS

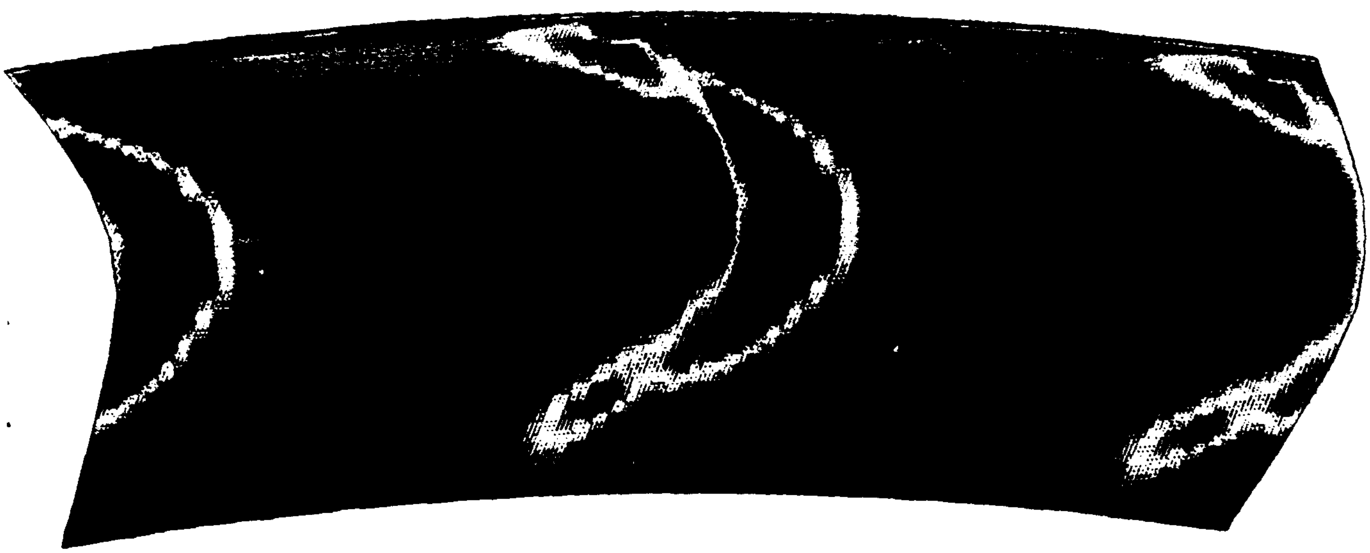


FIGURE 24 AREA TRAVERSE PREDICTION (3D NAVIER-STOKES)

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7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference
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8. Author 1 Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Harasgama, S.P.	Chana, K.S.		December 1990	22	4

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Turbines. Traversing. Pressure loss.

17. Abstract
Tests have been performed in the RAE Isentropic Light Piston Cascade (ILPC) facility to measure the total pressure loss of turbine nozzle guide vanes (NGV). A Three-Hole Non-Nulling probe has been utilised with a fast acting traverse which gives a full circumferential sweep over two blade wakes in approximately 500 to 700 ms.

Two types of probes have been used: the first with high frequency response sensors mounted within 25 mm of the probe tip, and the second with low response sensors mounted 500 mm away from the probe tip using lengths of pneumatic tubing.

It is shown that the first probe suffered significantly from probe aerodynamic perturbation due to vibration effects when the air stream was started up in the ILPC. It was found that analogue filtering was required at around 250 Hz in order for the NGV wakes to be distinguished. The wakes extracted after filtering were found to be quite distinct even at one axial chord downstream of the NGV. The second probe was found to be relatively free of aerodynamic perturbations due to the damping nature of the long length of pneumatic tubing between probe tip and transducer.

Results are presented for both probe types which indicate the wake decay between 0.2 and 1.0 axial chords downstream of NGV trailing edge. A full area traverse is also shown which indicates the areas of secondary flow downstream of the blade row.